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Nuclear Power Systems for Lunar and Mars Exploration

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NUCLEAR POWER SYSTEM FOR LUNAR AND MARS EXPLORATION

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Abstract

Initial studies of a variety of mission scenarios for the new Space Exploration Initiative, and the technologies necessary to enable or significantly enhance them, have identified the development of advanced space power systems - whether solar, chemical or nuclear - to be of prime importance.

Lightweight, compact, reliable power systems for planetary rovers and a variety of surface vehicles, utility surface power, and power for advanced propulsion systems were identified as critical needs for these missions. This paper discusses these mission scenarios, the concomitant power system requirements; the power system options considered and identifies the significant potential benefits of nuclear power for meeting the power needs of the above applications.

Introduction

One of the most rewarding of the uses of space for peace and progress is the exploration of space. Such exploration activities increase human presence beyond our terrestrial boundaries, increase knowledge, and provide substantial pride in human endeavors. Man has not visited an extraterrestrial surface since the end of the Apollo program in 1972. However, following Presidential leadership, the United States has a strong renewed interest in man's exploration of space.

In the President's July 20, 1990 remarks commemorating the 20th Anniversary of the Apollo 11 Moon Landing, the President charted a long term course for the human exploration of space. Beginning with the Space Station Freedom in the 1990's and, in the next century, returning to the moon, establishing a permanent presence, and using the experience and technologies gained from these missions to move on to the exploration and habitation of Mars. Following the President's speech, the NASA performed detailed studies of a variety of mission scenarios and architectures to accomplish these missions, and identified the key technologies needed to bring them to fruition.

The options studied considered various approaches such as: Vigorous Deployment and early landing on the moon; the earliest possible landing on Mars; reduced logistics from earth; delayed program start; and paced deployment.

The Exploration Option that received the most study and that will serve as the reference for this paper is depicted in Fig. 1. In this approach, we build upon our past and present investments in space such as Apollo, Shuttle and the Space Station Freedom, employ robotic and manned craft and emphasize science. The key point is, however, that we build a Lunar outpost first and learn to live on planetary surfaces before moving on to Mars. The Lunar/Mars exploration strategy will be implemented in three phases: emplacement, consolidation and operation. Thus, the power systems requirements evolve as the activities on the Lunar/Mars bases grow from an initial outpost to a self sufficient base. Following this philosophy a variety of power systems can be developed in a fashion timed to meet the required needs. Indeed, in the architectures discussed below the Lunar surface power systems evolve from solar at the initial low power levels to nuclear as the power needs grow. This approach allows adequate time for development of the high powered nuclear systems. In the following sections we will discuss the power system requirements, the power systems chosen to meet these requirements, and where applicable, the recommended technology development programs.

Power System Requirements

In the artists conception of a Lunar base shown in Fig. 2, one sees that there are a wide range of ongoing activities that require a variety of power systems. A stationary centralized power system is required to supply power for habitation and laboratory modules, science experiments, in-situ resource utilization, manufacturing and construction.

In addition, remote power systems are required for far-side observatories, science outposts and communications outposts; mobile power systems are required for pressurized and unpressurized rovers, excavation, regolith haulers, LEV payload unloaders, LEV services and auxiliary power carts. For the scenario considered herein, the Lunar base evolves from an initial habitat to the fully operational base shown in Fig. 3.

The stationary power requirements for this scenario are given in Table 1 as well as the initial requirements for a Mars base. Power requirements for a variety of Lunar rovers and a Mars exploration rover are given in Table 2 and power profiles for a few of these rovers are shown in Fig. 4. The figure shows some rover profiles have periods which could be used for recharge if energy storage power systems were used whereas others require some level of power continuously.

Power Systems

Stationary Power Systems

The approach to meeting the surface power needs which evolve from a few to hundreds of kilowatts electric was to initially use solar power systems for the lower power levels (25 kWe (day)/12.5 kWe (night)) and evolve to nuclear reactor systems for powers of 25 to 1000 kWe. This approach allowed us to meet the stated power needs in the required time frames for most of the scenarios studied. Other approaches included going directly to a combination of a reactor power system using static or dynamic conversion, together with a small photovoltaic or isotope system to supply emergency power.

It was found that advanced power system technologies were needed for both approaches. The present state-of-the-art for solar power systems is planar silicon (Si) solar arrays with a specific power of approximately 50 W/kg and nickel hydrogen ($Ni-H_2$) batteries with specific energies of approximately 50 W-hr/kg (100 percent depth of discharge). This is the technology being used to provide power for the Space Station Freedom. These power systems are attractive for low-Earth-orbit applications such as the Space Station Freedom but will be much too massive for Lunar and Mars surface applications due to the long day/night cycles. It was necessary to go to photovoltaic power systems using regenerative fuel cells to provide the initial Lunar power systems. The development of RFC energy storage systems would allow a twentyfold to fortyfold increase in specific energy over the present $Ni-H_2$ capability and advanced PVA could extend the specific power to 300 W/kg. These technologies would enable initial Lunar/Mars surface power systems in the 25 kWe range. Indeed, the use of these systems rather than the state-of-the-art silicon photovoltaic and nickel-hydrogen batteries reduces the initial mass in low Earth orbit (IMLEO) by 500 metric tons for the 25 kWe (day)/12.5 kWe (night) power system.

Similar IMLEO savings are made by using nuclear reactor space power systems rather than the advanced PV/RFC power systems as one moves to the larger power systems.

The mass savings in LEO for the advanced solar over SOA solar and nuclear over advanced solar systems are plotted in Fig. 5 as a function of power level. All results are for a 100 percent day/night cycle. The figure shows that IMLEO savings of over 1000 metric tons are accrued by going to the advanced solar and then the nuclear systems as the power needs evolve. A 1000-metric-ton reduction of IMLEO saves 15 HLV launches or approximately 8 billion dollars in launch costs.[1]

Figure 6 shows a layout of PVA/RFC power systems on a Lunar base.[2] Figure 7 shows one of our initial designs for an 825 kWe reactor space power system based on using the SP-100 reactor and free piston Stirling engines.[3] The reactor is located in a hole at the center of the power system. One can see from the figure that dominant feature of the overall system are the heat pipe radiator panels. A cross section of the reactor assembly is shown in Fig. 8, and Tables 3 and 4 give the power system performance and mass breakdowns, respectively.

Mobile/Remote Power Systems

A study[4] was made of power systems to meet the Mars rover requirement given in Table 2. Additional requirements for this power system included a 350 W-hr energy storage capability, a 5-yr life and no single point failures. The study of a wide variety of solar, reactor and isotopic power systems indicated that while the mission might possibly be accomplished using solar options, the least mass power systems were those based on Pu-238 isotopic heat sources. The isotopic systems all used the general purpose heat source (GPHS) shown in Fig. 9. Results were obtained for static radioisotopic thermoelectric generators (RTG's) at 6.1 and 7.5 percent efficiency and for dynamic isotope power systems (DIPS) using 1105 K Brayton and 1050 K free piston Stirling engine converters at 22 percent.

The masses for these systems are shown in Fig. 10. It is seen that while all the systems provide compact, lightweight power systems, the free piston Stirling engine option was the lightest system. It should also be mentioned that because of their higher efficiency the dynamic systems reduce the amount of Pu-238 required by about a factor of 3, thus reducing cost and radiological risk.

The free piston Stirling engine concept studied was a unique design where the GPHS isotope heat source was directly integrated with the Stirling heater heads. Figure 12 shows how such a power system might look mounted on the rover vehicle.

Fuel cell power systems were used to meet the requirements for some of the rovers identified in Table 2. They were recharged using a dynamic isotope or solar power source. However, a wide number of the vehicles are directly powered using the Brayton DIPS described in Fig. 13. The figure shows that this option provides a compact, stowable power system capable of continuous operation at these higher power levels. An artists conception of how this power system would be mounted on an unpressurized rover is shown in Fig. 14.

Direct Nuclear Propulsion

Direct nuclear propulsion technologies were also identified as critical for the space exploration initiative during the 90-day study. Both the solid core reactor (SCR) based on the successfully developed NERVA technology (Fig. 15) and the much more advanced gas core reactor (GCR) shown in Fig. 16 were investigated. The potential benefits to be accrued by the development of these technologies are shown in Fig. 17 where we have plotted the initial mass in LEO for a variety of propulsion system concepts and various specific impulses and trip times. The options considered are H_2-O_2 chemical combustion system with aerobreaking (CHEM/AB), solid core reactors with aerobraking (SCR/AB) and without aerobraking (SCR) and gas core reactor that are either regeneratively cooled or have radiators. The figure shows that the solid core and gas core reactors can reduce the required initial mass in low Earth orbit by 40 to 60 percent at a fixed trip time of 434 days. These propulsion systems also offer an attractive option if the aerobraking technology does not come to fruition. The figure also shows that using the very advanced gas-core technology could result in significantly reduced trip times. This is the primary reason for the renewed interest in this system.

Technology Development Programs

NASA already has the initial program elements in place to for the development of the key power systems needed for the Space Exploration Initiative. NASA has supported the tri-agency DOE/DOD/NASA SP-100 program for the development of the 100 kWe reactor space power system in the past and plans to increase this support in the upcoming years. In addition, NASA has an aggressive High Capacity Nuclear Power Program under the Civil Space Technology Initiative (CSTI). The goals and key elements of this program are shown in Fig. 18. The overall goal of this program is to extend the specific power and power level of space power systems using the SP-100 reactor from 21 to 80 W/kg and 100 to 800 kWe, through advancements in energy conversion, advanced radiators, power conditioning and control and materials. One of the major successes of this program is the progress in the development of free piston Stirling engines depicted in Fig. 19. In our efforts at NASA Lewis we have extended the state-of-the-art of free piston Stirling engines from 1.5 kWe piston and a specific mass of 280 kg/kWe in the RE-1000 engine to 12.5 kWe/piston at 12 kg/kWe in demonstrated performance in the dual piston 25 kWe space power demonstrator engine (SPDE). Since then we have completed the design of the next generation space Stirling engine (SSE) with 25 kWe/piston at 6 kg/kWe. This engine will be tested in the next few years. Similar significant advancements have also been made in the areas of advanced thermoelectrics and radiators.

In the area of initial solar surface power systems NASA will continue the efforts initiated in the Pathfinder Program.

The goals and requirements for this program are shown in Fig. 20. As the figure shows, we need to develop overall power systems with specific powers of approximately 3 We/kg on the Lunar surface and 8 We/kg on Mars. This means extending the capability of the photovoltaic energy conversion systems from 50 to 300 We/kg and increasing the energy storage capability from 50 to ~1000 W-hr/kg. The systems must also be able to operate for extended periods in the Lunar and Mars environments. The planned solar surface power program elements are shown in Fig. 21. They include efforts in advanced photovoltaics, regenerative fuel cells with gaseous and cryogenic reactant storage, thermal management and electrical power management. The majority of the effort to date has been on the development of the critically important regenerative fuel cells.

Concluding Remarks

An initial set of power system requirements for Lunar and Mars exploration have been identified. Advancements in both solar and nuclear space power systems are required to meet these requirements. The benefits of these technology developments are such that they are considered enabling technologies for this exploration. The initial elements of the surface power programs are presently in place. Plans for nuclear propulsion and rover power systems are being developed.

Acknowledgment

Much of the information in this report was generated during the NASA 90-day study by the NASA Headquarters Mars Technology Initiative Team (of which Mr. Sovie was a member) and the Planetary Surface Systems Team at Johnson Space Center (of which Mr. Bozek was a member). The authors wish to acknowledge the contributions of the other team members in assembling the information contained in this report.

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2. Kohout, L.L., "Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells," NASA TM-101980 presented at the International Conference on Space Power Conference sponsored by the International Aeronautical Federation, Cleveland, OH, June 5-7, 1989.

3. Mason, L.E., Bloomfield, H.S., and Hainley, D.C., "SP-100 Power System Conceptual Design for Lunar Base Applications," NASA TM-102090 presented at Sixth Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 8-12, 1989.

4. Bents, D.J., "Preliminary Assessment of Rover Power Systems for the Mars Rover Sample Return Mission," presented at the International Conference on Space Power sponsored by the International Aeronautical Federation, Cleveland, OH, June 5-7, 1989.

TABLE 1. - STATIONARY POWER SYSTEMS REQUIRED

Year	Power, kWe	Power, D/N	Mass, metric ton	Stowed volume, m^3
Lunar				
1	25	12.5	8.4	60
2	25	12.5	8.4	60
3	25	12.5	8.4	60
6	100	100	6.3	120
8	550	550	16.6	190
Mars				
15	25	25	2.5	5
16	75	75	7.5	15

TABLE 2. - TYPICAL ROVER POWER SYSTEM REQUIREMENTS

Task	Operating period[a]	Rover mass, metric tons	Average power, kWe	Peak power, kWe
Lunar				
LEVPU[b]	D	10 to 16	3	10
Unpressurized[c]	D/N	1.8	0.7[d]	3
Excavator	D	2.6	23	40
Hauler/truck	D	1.0	4	10
Pressurized	D/N	4.5	7	12
LEV servicer	D/N	1.8	2 to 10	10
Mars				
Exploration rover	D/N	0.5 to 1	0.5	2.5

[a]D = daylight only, D/N = daylight and/or night.
[b]16 metric tons includes Crane ancillary equipment.
[c]2 kWe for housekeeping, 8 kWe for thermal control and reliquifaction of O_2/H_2.
[d]Standby.

TABLE 3. - NUCLEAR POWER SYSTEM PERFORMANCE

Reactor thermal power, kWt	2500
Reactor design lifetime (at full power), yr	7
Electrical output (6 of 8 engines), kWe	825
Electrical output/operating engine, kWe	138
Rated electrical output/engine, kWe	150
Operating engine capacity, percent	91.7
Thermal-to-electric efficiency, percent	33.0
Stirling heater temperature, K	1300
Stirling temperature ratio	2.2
Stirling cooler temperature, K	591
Radiator surface temperature, K	525
Total heat rejected, kWt	1675
Lunar surface temperature (with apron), K	222
Lunar sky temperature, K	267
Radiator emissivity	0.85
Radiator area (spoked wheel), m^2	780

TABLE 4. - LUNAR BASE POWER SYSTEM MASS

Subsystem	Mass, kg
Reactor (2.5 MWt)	755
Instrumentation and control	359
Shadow shield	831
Primary heat transport	400
Reactor excavation bulkhead	549
Stirling engines	5 171
Engine support platforms	600
Heat rejection loops	550
EM pumps	80
Accumulators	15
Heat pipe radiator	2 500
PLR's and ac-dc converter	1 500
Transmission lines (5051 m)	917
Total mass	14 227
Total system specific mass, kg/kWe	17.2
Total system specific power, W/kg	58.0

Exploration approach

- Build upon past and present investments in space
  - Apollo, Viking, etc.
  - Space Shuttle
  - Space Station Freedom
- Employ robotic craft along with manned systems
- Emphasize science along the way
- Build a lunar outpost first
  - Research base for science and technology
  - Testbed for humans to Mars
- Explore Moon and Mars in phases
  - Emplacement → Consolidation → Operation
- Evolutionary approach to realizing Space Policy goal of
  "Expanding human presence and activity beyond Earth orbit into the solar system"

Figure 1.—Space exploration approach.

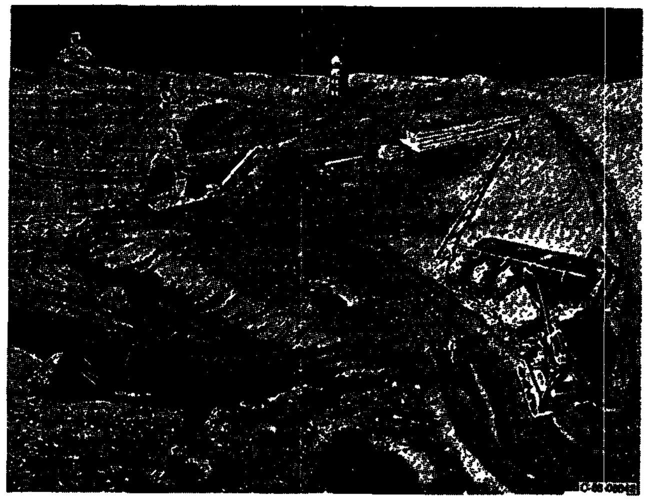


Figure 2.—Artist's conception of a lunar base.

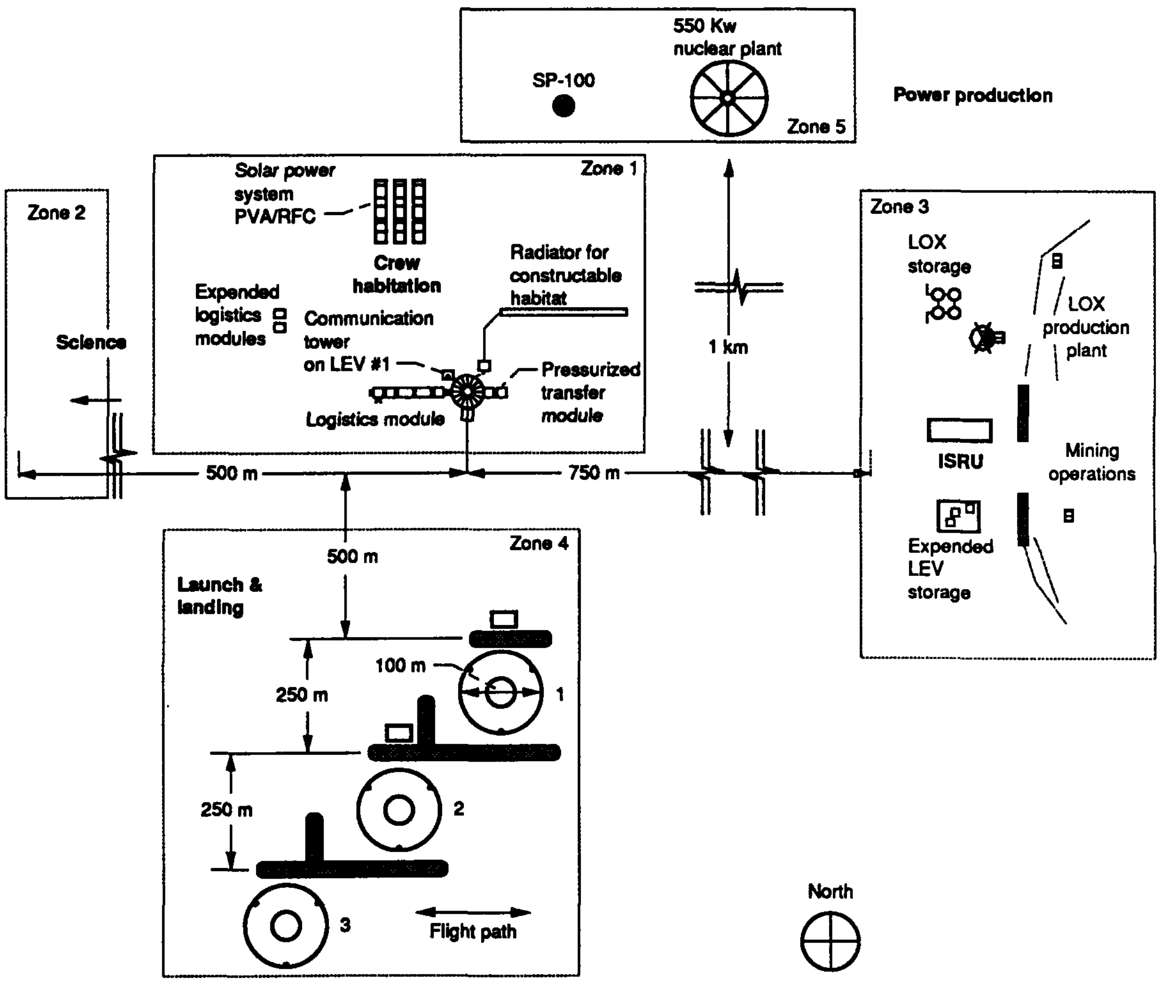


Figure 3.—Lunar base operational phase.

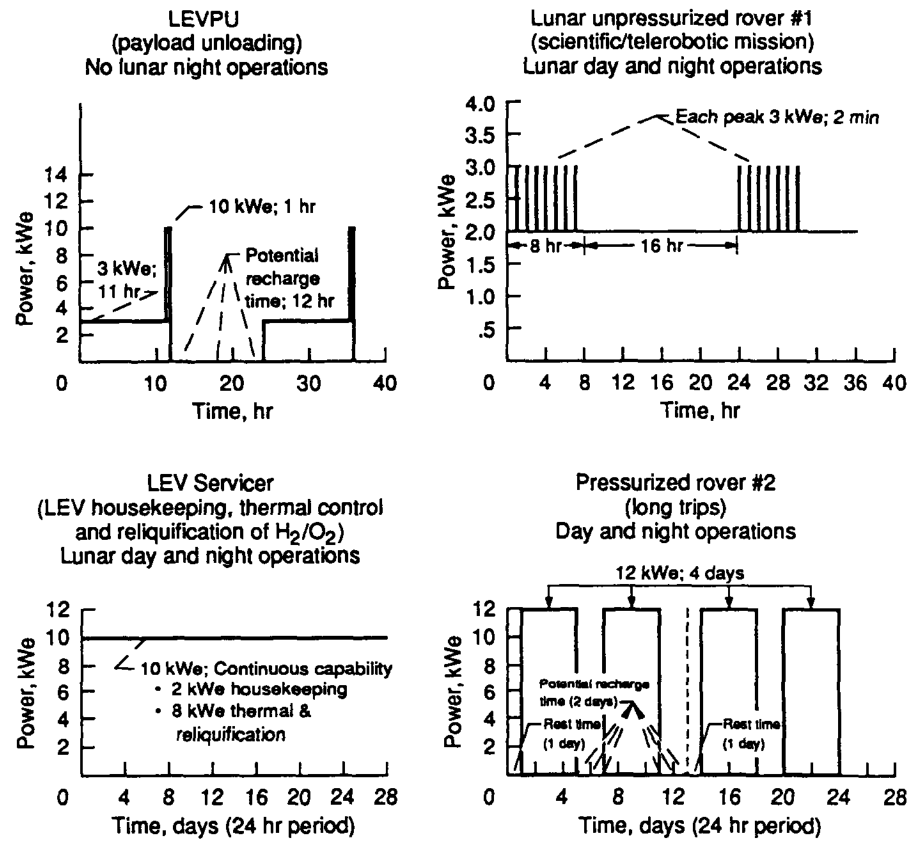


Figure 4.—Typical rover power profile requirements.

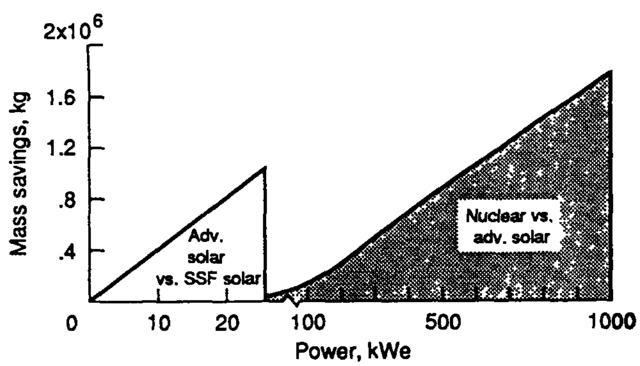


Figure 5.—Mass savings in LEO; adv. solar vs. Space Station Freedom solar, nuclear vs. adv. solar.

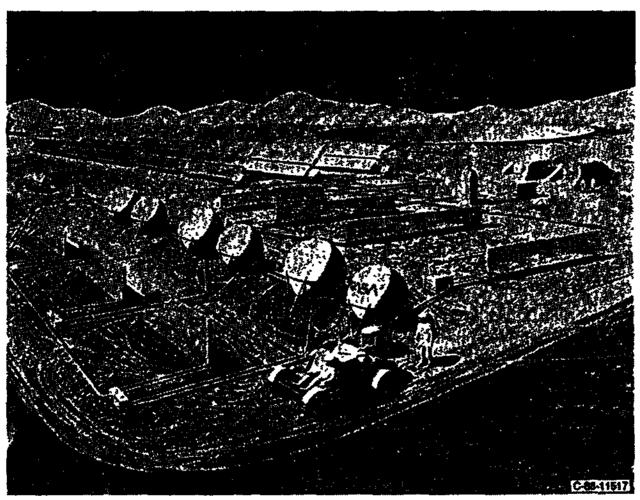


Figure 6.—Photovoltaic array/regenerative fuel cell lunar power system.

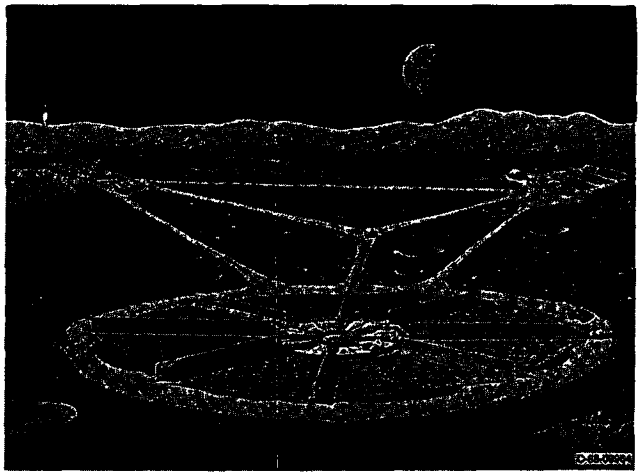


Figure 7.—825 kWe nuclear reactor space power system.

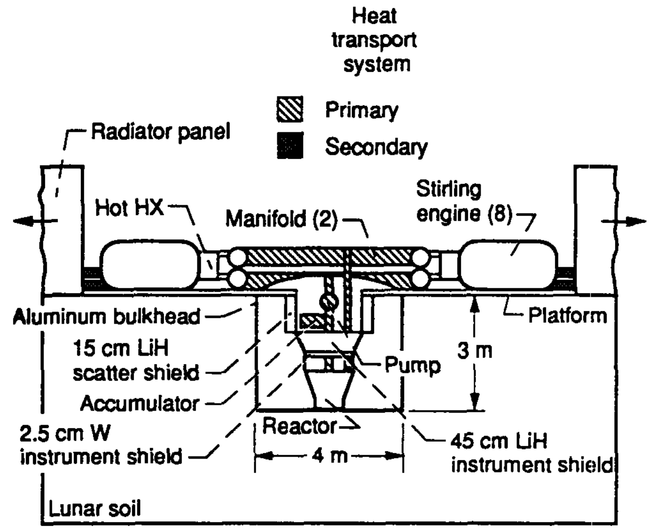


Figure 8.—Lunar base reactor assembly.

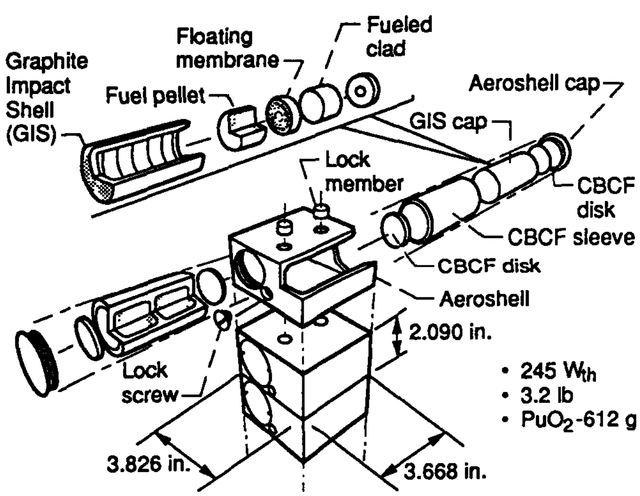
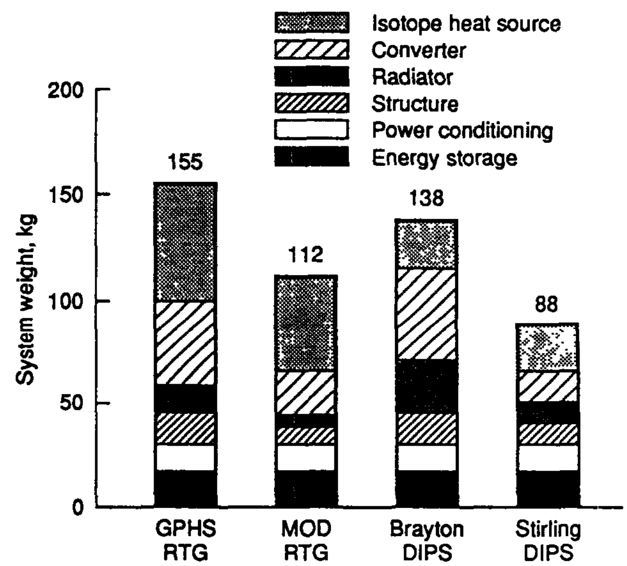


Figure 9.—General purpose heat source.



Power: 0.5 kWe/2.5 kWe peak, sink temperature 290 K

Figure 10.—Mars rover power system mass for various options.

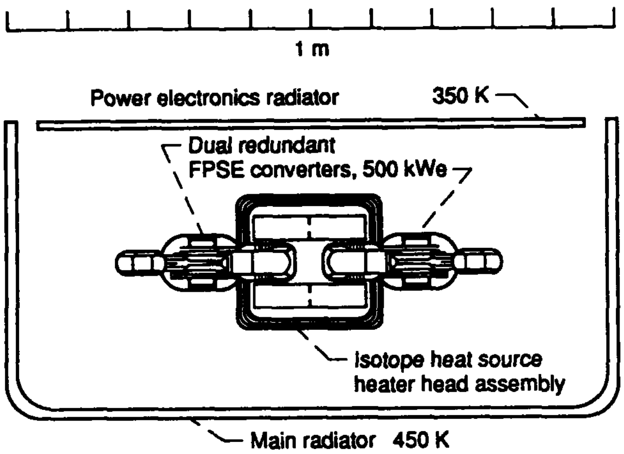


Figure 11.—Stirling dynamic isotope power system for a rover vehicle.

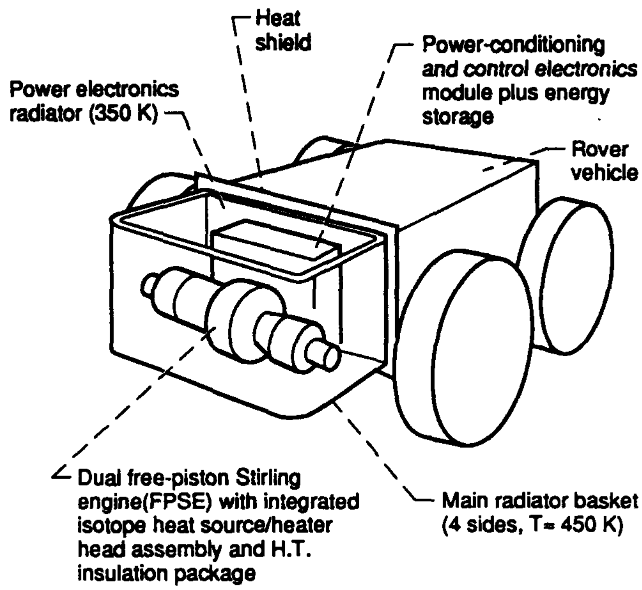
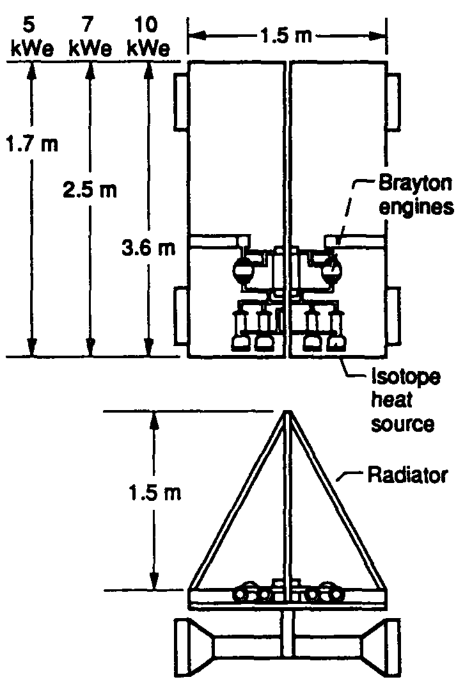


Figure 12.—Stirling dynamic isotope power system location in rover vehicle.



Advanced DIPS power cart

- GPHS Pu238 isotope heat source
- Closed Brayton cycle converter
  - Advanced technology (1300 K TIT)
  - One active engine; one spare
  - 16% efficient; min rad area design
- 6 kg/m^2 pumped loop radiator
  - One sided A-frame configuration
  - Sized for 370 K lunar sink temp.
- 98% efficient, 10 kg/kWe pwr cond.
- 10 year system life

	5 kWe	7 kWe	10 kWe
Pwr system mass, kg*	826	996	1104
Radiator area, m^2	5.8	8.2	12.0
Stowed vol.* m^3	.3	.45	.7
Deployed vol.* m^3	2	3	4

* Mass and volume of cart not included

Figure 13.—Advanced dynamic isotope power cart.

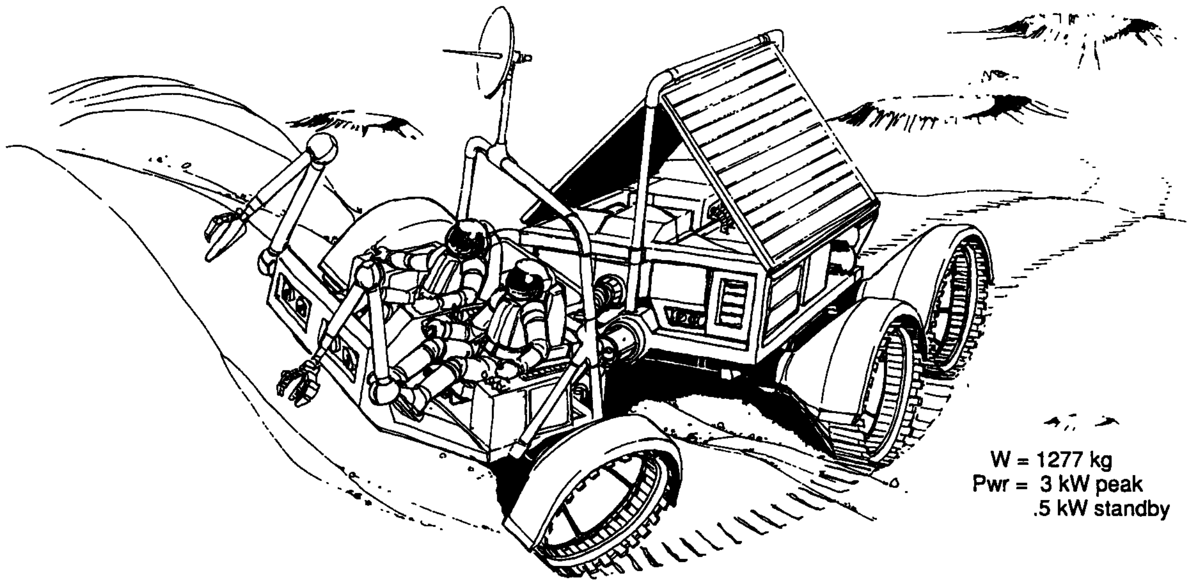


Figure 14.—Unpressurized rover with telerobot controller.

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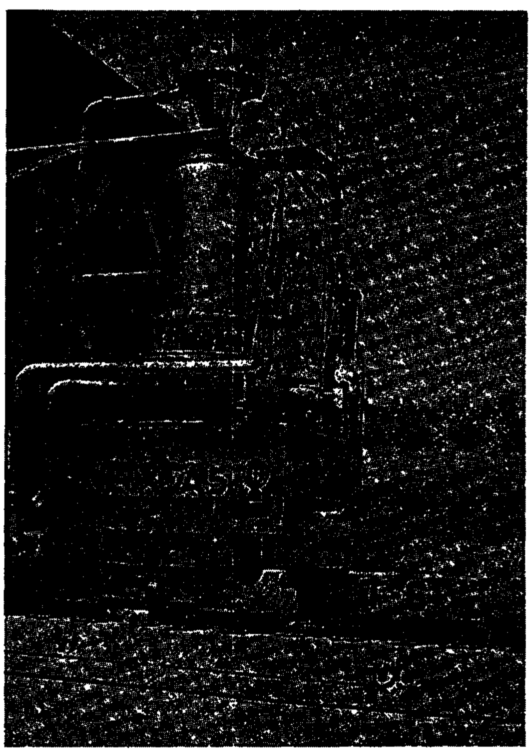

Figure 15.—The NRV rocket reactor-the XE prototype NERVA engine.

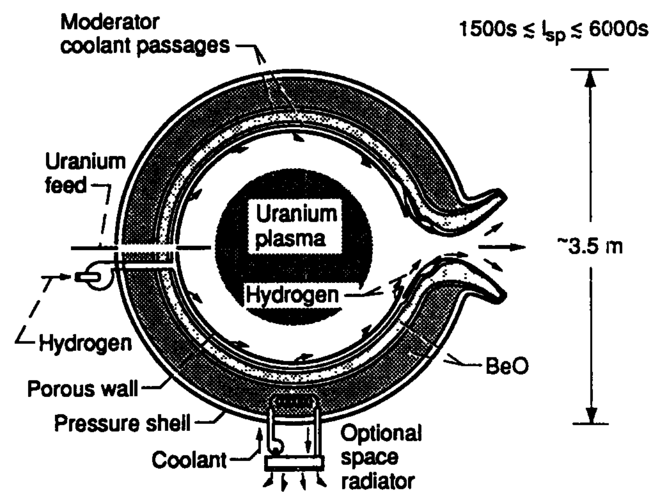

Figure 16.—High specific impulse, porous wall gas core engine concept.

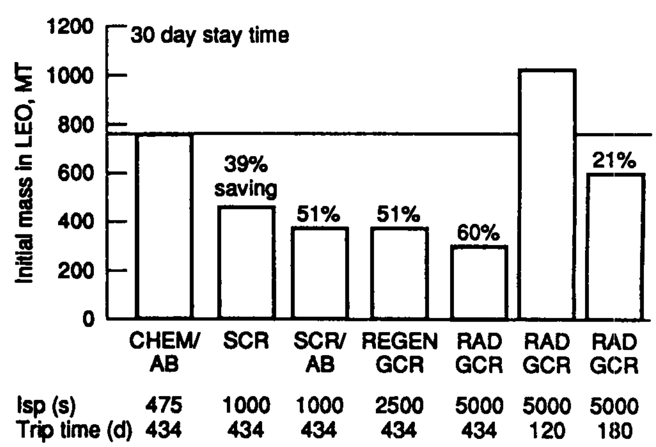

Figure 17.—Propulsion performance comparison; SCR and GCR piloted Mars missions, quick trips.

- Focused technology development to enhance capability of space power systems using GES reactor
  25 ⟶ 80 W/kg
  100 ⟶ 800 kWe
- Advanced energy conversion
  - Free piston Stirling engines
  - Advanced thermoelectrics
- Advanced radiators
- Power conditioning and control
- Refractory and composite materials

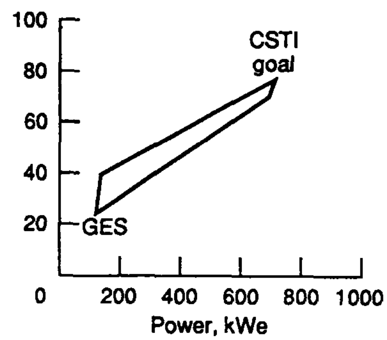

Figure 18.—High capacity nuclear power program; goals and program elements.

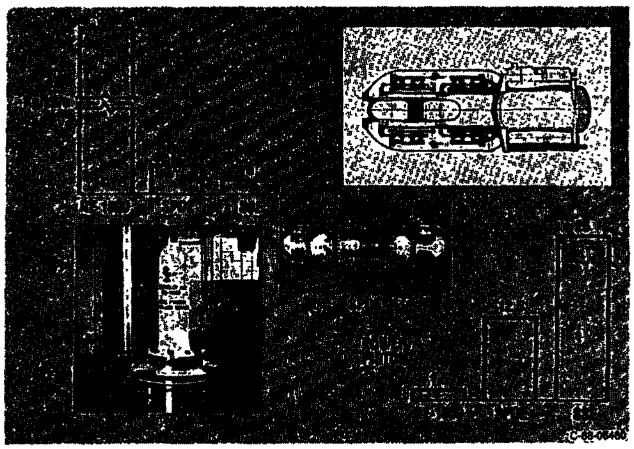

Figure 19.—Progress in FPSE development.

Goal: Demonstrate feasibility of critical component technologies necessary for initial lunar/Mars camps, spacecraft power systems

Requirements:	~3 We/kg - lunar camp	14 days	D/N cycle
	~8 We/kg - Mars camp	12 hr	D/N cycle

Energy conversion 40 ⟶ 300 W/kg
Energy storage 40 ⟶ 500-1000 Whr/kg
- Mission dependent

Potential for successful operation on Mars, lunar surfaces

Figure 20.—Solar surface power system goals and requirements.

- Photovoltaics
  GaAs
  - Single junction
  - Multi-junction
    - Deployable
    - Erectable
- Regenerative fuel cells
  - Proton exchange membrane
  - Alkaline
- Storage
  - Gaseous
  - Cryogenic
- Thermal management
- Power management/distribution

Figure 21.—Solar surface power program elements.

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16. Abstract

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